GEOINDICATORS

TOOLS FOR ASSESSING RAPID ENVIRONMENTAL CHANGES

ABSTRACT: The condition of the environment at any time reflects not only human influences but also natural processes and phenomena, which may be causing change whether or not people are present. The long evolutionary history of the Earth and the biosphere has been punctuated throughout by environmental changes that reduced or enhanced the capacity of terrestrial landscapes to provide a place for healthy life. Moreover, away from obvious sources of human disturbance (cities, waste disposal sites, mines, deforested areas), it may be extraordinarily difficult to separate the effects of human actions from those due to "background" natural processes.

A newly compiled checklist of geological indicators of rapid environmental change identifies 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators have been developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. As descriptors of common earth processes that operate in one terrestrial setting or another, geoindicators represent collectively a new kind of landscape metric, one that concentrates on the non-living components of the lithosphere, pedosphere, hydrosphere, and their interactions with the atmosphere and biosphere (including humans).

SOURCES: The geoindicator checklist has been developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Dr. Antony Berger, 528 Paradise St. VICTORIA BC V9A 5E2, chaired the Geoindicators Working Group. Ph/fax (604) 480-0840.

WHAT ARE GEOINDICATORS? Geoindicators are measures (magnitudes, frequencies, rates, and trends) of geological processes and phenomena occurring at or near the Earth's surface and subject to changes that are significant in understanding environmental change over periods of 100 years or less. They measure both catastrophic events and those that are more gradual, but evident within a human lifespan. Geoindicators can be used to monitor and assess changes in fluvial, coastal, desert, mountain and other terrestrial areas. They can also be used through paleoenvironmental research to unravel trends over the past few centuries and longer, thus providing important baselines against which human-induced and natural stresses can be better understood.

Geoindicators measure environmental change in terms that can be regarded as significant within the time span considered - presumably, not in amounts as low as parts per trillion (e.g. for contaminants) or as grams per square km (erosion), or rates as slow as a few mm per 1000 years (e.g. sea-levels). As defined, they do not apply to important earth processes that generally take place more slowly, such as diagenesis, metamorphism and deformation, and plate tectonic movements.

Geoindicators describe processes and environmental parameters that are capable of changing without human interference, though human activities can accelerate, slow or divert natural changes (e.g. Goudie 1990a, Turner et al. 1990). Humans are certainly an integral part of nature and the environment, but it is essential to recognize that nature and the environment are ever changing at one temporal and spatial scale or another, whether or not people are present. Environmental sustainability must, therefore, be assessed against a potentially moving background. Table 1 indicates the relative influence of human and natural (non-anthropogenic) stresses on geoindicators, though it excludes from consideration indirect changes brought about by global-scale, human-induced climate change. Table 1 also identifies those geoindicators that can, by reaching back into the recent geological past, help to establish the baseline against which contemporary change can be assessed and future change forecast.

Geoindicators have been developed from standard approaches used in geology, geochemistry, geophysics, geomorphology, hydrology and other earth sciences. For the most part the expertise and technology already exists (e.g. Cooke & Doornkamp 1990, Goudie 1990b). Some geoindicators are complex and costly, but many are relatively simple and inexpensive to apply.

The boundaries between geoindicators and other, non-geological, measures of environmental change and quality are not sharp, and some rather arbitrary choices were made in compiling this first checklist. For example, many chemical parameters needed to assess the quality of both surface and groundwater are included, because of the interdependency of surface water with other parts of the hydrological cycle: groundwater quality, streamflow, soil and sediment erosion, and even soil quality, karst activity, and wetlands water budget and geochemistry. On the other hand, the checklist excludes snow cover, which is an important determinant for runoff, soil moisture, soil creep, solifluction, frost action and avalanches.

TABLE 1. Geoindicators: natural vs. human influences, and utility for reconstructing past environments.

GEOINDICATOR	Natural Influence	Human Influence	Paleo reconstruction
Coral chemistry and growth patterns	H	H	H
Desert surface crusts and fissures	H	M	L
Dune formation and reactivation	H	M	M
Dust storm magnitude, duration and frequency	H	M	M
Frozen ground activity	H	M	H
Glacier fluctuations	H	L	H
Groundwater quality	M	H	L
Groundwater chemistry in the unsaturated zone	H	H	H
Groundwater level	M	H	L
Karst activity	H	M	H
Lake levels and salinity	H	H	M
Relative sea level	H	M	H
Sediment sequence and composition	H	H	H
Seismicity	H	M	L
Shoreline position	H	H	H
Slope failure (landslides)	H	H	M
Soil and sediment erosion	H	H	M
Soil quality	M	H	H
Streamflow	H	H	L
Stream channel morphology	H	H	L
Stream sediment storage and load	H	H	M
Subsurface temperature regime	H	M	H
Surface displacement	H	M	M
Surface water quality	H	H	L
Volcanic unrest	H	L	H
Wetlands extent, structure, and hydrology	H	H	H
Wind erosion	H	M	M

H - HIGHLY influenced by, or with important utility for
M - MODERATELY influenced by, or have some utility for
L - LOW or no substantial influence on, or utility for

Note: This table illustrates in a general way the relative roles of natural and human-induced changes, both direct and indirect, in modifying the landscape and its geological systems. However, it excludes from consideration influences that may be brought about by anthropogenically-induced climate change.

PRIORITIES: On a regional or global scale, some geoindicators are clearly more important than others. It is not difficult, for example, to rank soil and water quality indicators well ahead of subsurface temperature regime or desert surface crusts. However, apart from the mention in individual entries of some subsidiary indicators as primary or secondary (see groundwater quality, shoreline position), there is no prioritizing in this checklist. The approach has been to specify geoindicators that are important for specific environments, not to rank deserts (dune, dust storm, surface crusts and fissures) or coral reefs in importance relative to coastal zones or permafrost regions.

NATURAL HAZARDS: Geoindicators measure processes that produce perceptible results within a century. They are concerned more with the build-up to such singular events as earthquakes and volcanic eruptions, rather than the events themselves. It should be noted that change in many geoindicators takes place during infrequent, extreme events (e.g. floods, sinkhole collapse, landslides, eruptions, faulting), which are difficult to capture by routine monitoring.

Geoindicators are not directly concerned with mitigating the effects of natural disasters. Thus, a volcanic eruption is not itself an indicator in the sense used here, but rather a particular expression of a continuing natural process, volcanicity. The volcanic unrest geoindicator describes the thermal, structural, and geomorphological state of a region liable to erupt. Likewise, a single earthquake is not a geoindicator: the well-known seismicity geoindicator reflects the state of stress and its release within specific regions of the Earth's crust, which may or may not lead to an obvious earthquake. Tsunamis, those seismically-generated waves that can produce so much damage to coastal areas, are not geoindicators, and neither are landslides, per se, but rather the state of slopes likely to fail. Parameters that assess soil erosion are included, but a single river flood is not - though the frequency of flooding is implicit in the streamflow geoindicator.

GEOINDICATORS AS AUTOMATIC RECORDING STATIONS: Some geoindicators have the capacity to record and store evidence of environmental changes. Examples include speleothem growth patterns (karst activity), ice layers, subsurface temperature regimes, lake sediment geochemistry, and corals. Though their main value is as paleoclimatic archives, they have an important application to long-term monitoring of environments where it is not possible, for reasons of cost, personnel or remoteness, to install recording instruments. Such geoindicators provide ‘automatic recording stations’ that can be invaluable as registers of contemporary environmental change, for they function without human intervention, even if de-coding the record is sometimes costly. They can, to a degree, be regarded as comparable to weather or seismic stations, which record their data on tapes that are collected from time to time and shipped off for analysis. Such natural recording stations can be sampled at intervals to determine how their environment has changed. Thus, one may revisit a remote lake every decade to extract a ten-year record from the sediment layer of airborne particulates or of changes in watershed erosion rate. The near-surface thermal profile beneath an abandoned forest clear-cut could be used to determine a record of recent changes in soil temperature.

THE GEOINDICATOR CHECKLIST: The Twenty-seven geoindicators are available in the form of a checklist or menu with sixteen fields for each indicator. Appropriate indicators can be selected depending on the terrain and the environmental issues under consideration. The following list contains the 27 geoindicators with 3 descriptor fields for each.

Coral chemistry and growth patterns

Significance: The combination of abundant geochemical tracers, sub-annual time resolution, near-perfect dating capacity, and applicability to both current and past climatic changes establishes corals as one of the richest natural environmental recorders and archives. A 30 cm-diameter coral colony growing at an average rate of 1 cm/yr will provide 20-25 years of baseline data, whereas massive colonies 3-6 m high may provide historical data for extensive tracts of tropical ocean, such as are not otherwise available.

Human or Natural Cause: Corals respond to both natural changes in the marine environment and to anthropogenic pollution.

Applications to Past and Future: Corals are widely-distributed, natural, continuous data-loggers (automatic recording stations) whose records can be read (played back) over centuries, if they are old enough, or over just the last few months. They are an invaluable source of paleoenvironmental information for tropical coastal areas and the shallow marine realm.

Desert surface crusts and fissures

Significance: Desert surface crusts are important because they protect the underlying fine material from wind erosion.

Human or Natural Cause: The formation of surface crusts is related primarily to natural causes, but hydrological regimes that affect crust formation and persistence may be altered by human activities, such as river diversion and groundwater extraction.

Applications to Past and Future: The thickness, composition and number of evaporitic crusts may indicate past patterns of local and regional precipitation and temperature.

Dune formation and reactivation

Significance: Moving dunes may engulf houses, fields, settlements and transportation corridors. Active dunes in sub-humid to semi-arid regions decrease arable land for grazing and agriculture. They also provide a good index of changes in aridity. Coastal dunes are important determinants of coastal stability, supplying, storing and receiving sand blown from adjacent beaches. Dunes play an important role in many ecosystems (boreal, semi-arid, desert, coastal) by providing morphological and hydrological controls on biological gradients.

Human or Natural Cause: Changes in dune morphology and movements can result from variations in aridity (drought cycles). Widespread changes can also be induced by changes in wind patterns and by human disturbance, such as alteration of beach processes and sediment budgets, destruction of vegetation cover by trampling or vehicle use, overgrazing, and the introduction of exotic species.

Applications to Past and Future: A record of dune activity for the last 50 years can be constructed for many semi-arid areas and correlated with temperature and precipitation records. Paleorecords, including paleowind directions, exist for relict Quaternary dunes, which are widespread in Africa, Australia, India and North America. The potential impact of future climatic variability on eolian systems may also be assessed.

Dust storm magnitude, duration, and frequency

Significance: Local, regional and global weather patterns can be strongly influenced by accumulations of dust in the atmosphere. Dust storms remove large quantities of surface sediments and topsoil with nutrients and seeds: in the 1930s, drought and dust storms created the 'Dust Bowl', greatly reducing agricultural production on the North American prairies at that time. Wind-borne dust, especially where the grain size is less than 10 µm, and salts are known hazards to human health. Dust storms are also an important source of nutrients for soils in desert margin areas.

Human or Natural Cause: Dust storms are natural events, but the amount of sediment available for transport may be related to surface disturbances such as overgrazing, ploughing, or removal of vegetation.

Applications to Past and Future: Good index of aridity and/or wind speeds. Paleo-records may be developed from ancient dust storm deposits found in ice cores, ocean sediments and loess.

Frozen ground activity

Significance: Permafrost influences natural and managed ecosystems, including forests, grasslands and rangelands, mountains and wetlands, and their hydrological systems. It is an agent of environmental change that affects ecosystems and human settlements. Permafrost may enhance further climate change by the release of carbon and other greenhouse gases during thawing. It is estimated that nearly 1/4 of the world's terrestrial carbon is tied up in dead organic mater in the active layer and in permafrost: long-term climate warming would facilitate decomposition and drying, releasing huge quantities of methane and CO_2 [see wetlands extent, structure and hydrology]. Permafrost can result in serious and costly disruptions from ground subsidence, slope failure, icings, and other cryogenic processes.

Human or Natural Cause: The freezing and thawing of soils and surficial materials and the consequent ground changes are natural processes controlled by climatic conditions, and can be modified by human actions in and around settlements and engineering works.

Applications to Past and Future: Permafrost and cryogenic features are selective recorders of climate change through their thermal and stratigraphic record. Fossil features formed during previous freeze and thaw episodes can be used to indicate and even date the former presence of permafrost, whereas degradational landforms in current permafrost areas indicate either former warm periods or current thermal instability.

Glacier fluctuations

Significance: Glaciers are highly sensitive, natural, large-scale, representative indicators of the energy balance at the Earth's surface in polar regions and high-altitudes. Their capacity to store water for extended periods exerts significant control on the surface water cycle. The advance and retreat of mountain glaciers creates hazards to nearby human structures and communities through avalanches, slope failure, catastrophic outburst floods from ice and moraine-dammed lakes. Notwithstanding local glacier advances, the length of mountain glaciers and their ice volume has decreased throughout the world during the past century or two, providing strong evidence for climate warming, though there may also be local correlations with decreasing precipitation. It is estimated that the European Alps have lost more than half their ice in the past century

Human or Natural Cause: Glaciers grow or diminish in response to natural climatic fluctuations. They record annual and long-term changes and are practically undisturbed by direct human actions.

Applications to Past and Future: Changes in glaciers in areas of high snowfall may provide early clues to the onset of climate change. Ice and air bubbles trapped between ice crystals in glaciers and ice-sheets provide an invaluable archive of past climates, which extends, in Greenland, the Antarctic and certain mountain glaciers, well back into the Pleistocene. They also contain a record of past changes in atmospheric composition, including trace gas concentrations, chemical impurities of terrestrial and marine origin, cosmogenic isotopes, extraterrestrial material, and aerosols of volcanic, desert and human origin. The chronostratigraphy of snow-avalanche deposits may also be an important source of paleoclimate information (snowfall, wind) in mountain areas.

Groundwater quality

Significance: Groundwater is almost globally important for human consumption, and changes in quality can have serious consequences. It is also important for the support of habitat and for maintaining the quality of baseflow to rivers. The chemical composition of groundwater is a measure of its suitability as a source of water for human and animal consumption, irrigation, and for industrial and other purposes. It also influences ecosystem health and function, so that it is important to detect change and early warnings of change both in natural systems and resulting from pollution.

Human or Natural Cause: Both. Changes in natural baseline conditions may occur over the timescales of interest, and may be measured at an individual borehole or spring. Superimposed on these, however, are the greater impacts of the human activities described above.

Applications to Past and Future: Below the water table, groundwater is not generally a good archive of past changes because of dispersion of the input signal. However, paleowaters may be recognized by chemical and isotopic signals in large sedimentary basins. Around springs, deposits of calcareous or siliceous material (travertine, tufa, sinter), ranging from those that are inorganically precipitated to those that are wholly organic, may reflect past changes in surface climate or in local underground conditions of hydrology and chemistry. The chemistry of groundwater in the unsaturated zone can provide a key archive of past climatic and ecological changes [see groundwater chemistry in the unsaturated zone].

Groundwater chemistry in the unsaturated zone

Significance: Changes in recharge rates have a direct relationship to water resource availability. The unsaturated zone may store and transmit pollutants, the release of which may have a sudden adverse impact on groundwater quality.

Human or Natural Cause: Both. Depending on land use, the unsaturated zone beneath a site may record either natural inputs from the atmosphere, vegetation, soil or mineral weathering, or the effects of human activities such as agriculture and industrial activity, or regional problems such as acidic deposition.

Applications to Past and Future: The record in the unsaturated zone may indicate inputs (amounts of recharge, history of recharge or contamination) over periods of 10-100 years, and possibly up to 500 years or more. The resolution of the signal will be related to dispersion. Under favourable conditions (e.g. in semi-arid environments), the unsaturated zone may provide an important terrestrial record of climate/environmental change.

Groundwater level

Significance: Groundwater is the major source of water in many regions, supplying a large proportion of water globally. In the USA, more than half the drinking water comes from the subsurface: in arid regions it is generally the only source of water. The availability of clean water is of fundamental importance to the sustainability of life. It is essential to know how long the resource will last and to determine the present recharge: groundwater mining is a terminal condition.

Human or Natural Cause: There are natural changes in groundwater levels because of climate change (drought, pluvial episodes), but the main changes are due to human abstraction. In many places artificial recharge of aquifers is accomplished deliberately by pumping or as an indirect result of irrigation.

Applications to Past and Future: Paleowaters may provide an archive of past climatic variations.

Karst activity

Significance: It is estimated that karst landscapes occupy up to 10% of the Earth's land surface, and that as much as a quarter of the world's population is supplied by karst water. The karst system is sensitive to many environmental factors. The presence and growth of caves may cause short-term problems, including bedrock collapse, disparities in well yields, poor groundwater quality because of lack of filtering action, instability of overlying soils, and difficulty in designing effective monitoring systems around waste facilities. Instability of karst surfaces leads annually to millions of dollars of damage to roads, buildings and other structures in North America alone. Radon levels in karst groundwater tend to be high in some regions, and underground solution conduits can distribute radon unevenly throughout a particular area.

Human or Natural Cause: Karst processes are naturally occurring. They can be influenced by human activities such as land-use modification (e.g. deforestation), waste disposal, and opening or blocking of cave entrances, all of which can substantially affect sedimentation, speleothem deposition and groundwater quality over the short term. Overgrazing in Europe several centuries ago caused severe erosion of soils in many karst areas, leaving only bare, fissured rock surfaces. Although most sinkhole collapse is triggered by high discharge of underground streams, lowering of water tables by overpumping in areas underlain by thick soils or weak rocks can induce ground failure and collapse into subsurface voids.

Applications to Past and Future: Karst responds with great sensitivity to environmental changes, and karst features (especially speleothems) contain many clues to past climatic and hydrological events and changes at a variety of time scales. It is uncertain whether future conditions can be interpreted from karst features, because many changes tend to be abrupt and discontinuous.

Lake levels and salinity

Significance: The history of fluctuations in lake levels provides a detailed record of climate changes on a scale of ten to a million years. Lakes can also be valuable indicators of near-surface groundwater conditions.

Human or Natural Cause: Natural, but can be influenced by human-induced climate change, and by engineering works, such as dams and channels. For example, as a result of diversion into irrigation projects of rivers that flowed into the formerly stable Aral Sea between Kazahkstan and

Uzbekistan, the volume and extent of this huge inland lake has been dramatically reduced: between 1960 and 1989 its level dropped by 14 m, its volume decreased by 68%, and its salinity tripled.

Applications to Past and Future: Good index of water balance and changes in precipitation and evaporation. Records of lake dynamics in historic and pre-historic periods provide baseline data on past responses to climate change. With the establishment of threshold values, lakes may provide an early warning of shallow groundwater depletion.

Relative sea level

Significance: Changes in RSL may alter the position and morphology of coastlines, causing coastal flooding, waterlogging of soils and a loss or gain of land. They may also create or destroy coastal wetlands and salt marshes, inundate coastal settlements, and induce salt-water intrusion into aquifers, leading to salinization of groundwater. Coastal ecosystems are bound to be affected, for example, by increased salt stress on plants. A changing RSL may also have profound effects on coastal structures and communities. Low-lying coastal and island states are particularly susceptible to sea-level rise. It is estimated that 70% of the world's sandy beaches are affected by coastal erosion induced by RSL rise.

Human or Natural Cause: Variations in sea levels are natural responses to climate change, geoidal variations, movements of the sea floor, and other earth processes outlined above. It has been suggested that human actions including drainage of wetlands, withdrawal of groundwater (which eventually flows to the sea), and deforestation (which reduces terrestrial water storage capacity) may currently contribute about 0.5 mm/year to a global rise in sea level. Human-induced climate change is also of obvious importance. Local changes may be caused by large engineering works nearby, such as river channelling or dam construction, that influence sediment delivery and deposition in deltaic areas.

Applications to Past and Future: Changes in Holocene RSL, especially over the past 1000 years, can be resolved on the order of centuries and may be useful for predicting future trends and effects. Modern RSL provides a basis for estimating future levels, though local variations may also be caused by temporal events, such as earthquakes.

Sediment sequence and composition

Significance: The chemical, physical and biological character of aquatic sediments can provide a finely resolvable record of environmental change, in which natural events may be clearly distinguishable from human inputs.

Human or Natural Cause: Sediment deposition is a natural process which can be strongly influenced by human activities (e.g. land clearing, agriculture, deforestation, acidification, eutrophication, industrial pollution) within the drainage basin or sediment catchment.

Applications to Past and Future: Analysis of sediment sequence and composition is primarily used for paleoenvironmental reconstructions. Pollen, diatoms, spores, algae, and certain other micro- and macrofossils in water-laid sediments provide information about changes in composition and spatial pattern of Late Quaternary vegetation that can be used to infer regional paleoclimatic trends. The geochemical and physical character of the sediments can also provide a record of 'baseline' changes in natural and human activities within and outside the drainage basin. This is a source of valuable data on pre-industrial environments, and on agricultural impacts on water resources, and it can provide a basis for watershed planning.

Seismicity

Significance: Earthquakes constitute one of the greatest natural hazards to human society. Between 1960 and 1990 earthquakes killed about 439,000 people worldwide and caused an overall economic loss of some $US 65 billion. The 1994 Northridge earthquake in California alone resulted in over US$30 billion in property damage, and the 1995 Kobe earthquake over $100 billion. Surface effects include uplift or subsidence, surface faulting, landslides and debris flows, liquefaction, ground shaking, and tsunamis ('tidal' waves caused by undersea tremors). Damage to buildings, roads, sewers, gas and water lines, power and telephone systems, and other built structures commonly occurs.

Human or Natural Cause: Earthquakes are predominantly natural events. However, shallow-focus seismic tremors can be induced by human actions that change near-surface rock stresses or fluid pressures. These actions include: extracting (or pumping back into the ground for storage or for secondary hydrocarbon recovery) water, gas, petroleum, waste fluids; mining or quarrying activities; and loading the surface with large water bodies (reservoirs). Underground explosions, particularly for nuclear testing, can also generate seismic events.

Applications to Past and Future: Seismic records for the past century are available for many parts of the Earth. Extending this record through historical and paleoenvironmental studies may be important in establishing spatial and temporal patterns of significant seismicity. Despite many efforts, there is still no assured method for predicting when earthquakes will occur. Increases and impending release of crustal stresses may be indicated by certain geological and geophysical precursors, including fluctuations in water table levels in wells, changes in geomagnetic fields, piezoelectric effects, and ground surface tilting, shortening and displacement.

Shoreline position

Significance: Changes in the position of the shoreline affect transportation routes, coastal installations, communities, and ecosystems. The effects of shoreline erosion on coastal communities and structures can be drastic and costly. It is of paramount importance for coastal settlements to know if local shorelines are advancing, retreating or stable. Rates of recession as high as 5-10 m/yr have been measured in many places around the world, and much higher rates have been recorded locally. Coastal erosion in the USA alone is estimated to cost $700 million annually. Floods related to recent storm surges along the low-lying coasts of the Bay of Bengal have caused as many as 50,000 deaths per event.

Human or Natural Cause: Erosion and sediment accretion are on-going natural processes along all coasts. Human activities (e.g. dredging, beach mining, river modification, installation of protective structures such as breakwaters, removal of backshore vegetation, reclamation of nearshore areas) can profoundly alter shoreline processes, position and morphology, in particular by affecting the sediment supply.

Applications to Past and Future: In general, coastal phenomena can be reliably anticipated only where extensive research and monitoring data exist. A lack of current change is no assurance of continued stability in the future, but information on changes in the shoreline position, especially over the longer term, may be useful for short-term empirical predictions. Monitoring shorelines and coastal sediment dynamics may provide a better understanding of the responses of the shoreline to human modifications and sea-level change.

Slope failure (landslides)

Significance: Thousands of people are killed each year by landslides: in China and Peru, tens of thousands of deaths have resulted from single landslides. Annual property damage from landslides worldwide is estimated in the tens of billions of dollars, with more than $1.5 billion in annual losses in the USA alone. There are innumerable small to medium-size slope failures that cumulatively impose costs to society as great or greater than the large infrequent catastrophic landslides that draw so much attention. Damage to ecosystems has not generally been documented, but landslides may destroy habitats, for example by blocking streams and denuding slopes.

Human or Natural Cause: Slope failure is a natural process which can be induced, accelerated or retarded by human actions. Many causes are involved including:

1. Removal of lateral support through the erosive power of streams, glaciers, waves, and longshore and tidal currents; through weathering, and wetting, drying and freeze-thaw cycles in surficial materials; through land subsidence or faulting that creates new slopes; and through human actions such as cutting slopes for roads and other structures, quarrying, removal of retaining walls, and lowering of reservoirs.
2. Adding weight naturally to slopes by rain, hail, snow and water from springs, by accumulation of talus or volcanic debris, and by human actions such as landfills, stockpiles of ore or rock, waste piles, construction of heavy building and other structures, and water leaking from pipelines, sewers, canals, and reservoirs.
3. Earthquakes, thunder, vibrations from nearby slope failures, and human activities such as vibrations from explosions, machinery, road and air traffic.
4. Regional tilting that increases slope angles.
5. Decrease of underlying support by subrosion and removal of granular and soluble materials [see karst activity], mining, loss of strength or failure and/or squeezing out of underlying

material.

6. Lateral pressure from water in cracks and caverns, freezing of water in cracks, hydration of minerals, and mobilization of residual stress.

7. Volcanic processes that modify ground and rock stresses, such as inflation or deflation of magma chambers, fluctuations in lava-lake levels, and increase in ground tremors.

Applications to Past and Future: Dating cracks and their subsurface extension, subsidence and upheavals, and other features associated with landsliding can provide clues about past climatic changes and associated denudation rates, and the relative significance of rainfall, earthquake, and volcanic triggers for past slope failures. This knowledge, if aided by regional and temporal monitoring of crack development, can be used to forecast future landslide activity.

Soil and sediment erosion

Significance: Soil erosion is an important social and economic problem and an essential factor in assessing ecosystem health and function. Estimates of erosion are essential to issues of land and water management, including sediment transport and storage in lowlands, reservoirs, estuaries, and irrigation and hydropower systems. In the USA, soil has recently been eroded at about 17 times the rate at which it forms: about 90% of US cropland is currently losing soil above the sustainable rate. Soil erosion rates in Asia, Africa and South America are estimated to be about twice as high as in the USA. FAO estimates that 140 million ha of high quality soil, mostly in Africa and Asia, will be degraded by 2010, unless better methods of land management are adopted.

Human or Natural Cause: Erosion is a fundamental and complex natural process that is strongly modified (generally increased) by human activities such as land clearance, agriculture (ploughing, irrigation, grazing), forestry, construction, surface mining and urbanization. It is estimated that human activities have degraded some 15% (2000 million ha) of the earth's land surface between latitudes 72^{o}N and 57^{o}S. Slightly over half of this is a result of human-induced water erosion and about a third is due to wind erosion (both leading to loss of topsoil), with most of the balance being the result of chemical and physical deterioration [see soil quality].

Applications to Past and Future: Knowledge of past soil erosion rates under undisturbed conditions provides a basis for understanding downstream and downslope landforms and processes. Where surface disturbance has occurred, information about present and possible future erosion rates furnishes a basis for reducing the adverse effects of accelerated soil erosion. In particular, measurements of erosion resulting from agricultural disturbance provide the means for developing technology to minimize loss of topsoil and maximize crop productivity over extended periods.

Soil quality

Significance: As one of Earth's most vital ecosystems, soil is essential for the continued existence of life on the planet. As sources, stores, and transformers of plant nutrients, soils have a major influence on terrestrial ecosystems. Soils continuously recycle plant and animal remains, and they are major support systems for human life, determining the agricultural production capacity of the land. Soils buffer and filter pollutants, they store moisture and nutrients, and they are important sources and sinks for CO_2, methane and nitrous oxides. Soils are a key system for the hydrological cycle [see groundwater chemistry in the unsaturated zone]. Soils also provide an archive of past climatic conditions and human influences.

Human or Natural Cause: Soils may be degraded or enhanced by both natural processes and human activities. Human activities influence soil properties by causing increases in bulk density from agricultural tillage and road operations and in acidification from inorganic fertilizers and acid rain. Soil degradation is one of the largest threats to environmental sustainability: over the past half century the productivity of more than 1.2 billion ha of land (an area larger than China and India together) has been significantly lowered. It is estimated that about 15% of the soils between latitudes 72^{o}N and 57^{o}S have been degraded by human activities.

Applications to Past and Future: The morphology and chemistry of soils as determined in soil profiles may record past changes in the environment as, for example, iron oxides that accumulated due to flooding of low-lying areas, charcoal fragments produced by forest fires, or pottery shards produced by early humans. The properties of older soils (paleosols), whether buried or not, are indicators of past climates and can be used to predict the impacts of future climatic changes. High rainfall periods causing weathering and leaching are manifested in the clay content and mineralogy, clay coatings and the silica/sesquioxide ratio. Granular soil structures can result from biological activities associated with grasslands ecosystems or from frost action.

Streamflow

Significance: Streamflow directly reflects climatic variation. Stream systems play a key role in the regulation and maintenance of biodiversity. Changes in streams and streamflow are indicators of changes in basin dynamics and land use. One estimate puts the total annual losses to the economy from flooding of river and coastal plains worldwide at US$20,000 million.

Human or Natural Cause: Natural variations in streamflow predominate, but they can be strongly modified by human actions. It is estimated that about 3/4 of the total water flow of the 139 largest river systems in North America, Europe and the former Soviet Union is significantly affected by dams and reservoirs, irrigation, and diversion for use outside the watershed.

Applications to Past and Future: Estimates of paleofloods and paleodischarge can sometimes be made through study of stream sediment deposits, channel morphology, and associated landforms.

Stream channel morphology

Significance: Channel dimensions reflect magnitude of water and sediment discharges. In the absence of hydrologic and streamflow records, an understanding of stream morphology can help delineate environmental changes of many kinds. Changes in stream pattern, which can be very rapid in arid and semi-arid areas, place significant limits on land use, such as on islands in braided streams and meander plains, or along banks undergoing erosion.

Human or Natural Cause: Significant changes in stream dimensions, discharge and pattern may reflect human influences such as water diversion and increased sediment loads resulting from land clearance, farming, or forest harvesting. Such variations are also responsive to climatic fluctuations and tectonics.

Applications to Past and Future: Data can be used for predictions of up to about 10 years.

Stream sediment storage and load

Significance: Sediment load determines channel shape and pattern [see stream channel morphology]. Changes in sediment yield reflect changes in basin conditions, including climate, soils, erosion rates, vegetation, topography and land use. Fluctuations in sediment discharge affect a great many terrestrial and coastal processes, including ecosystem responses, because nutrients are transported together with the sediment load. For example, to reproduce effectively, salmon and trout need gravel stream beds for spawning and egg survival; silt and clay deposits formed by flooding or excessive erosion can destroy these spawning beds. Stream deposits also represent huge potential sinks for, and sources of, contaminants.

Human or Natural Cause: Natural, but influenced strongly by human actions, such as in the construction of dams and levees, forest harvesting and farming in drainage basins. The current annual sediment load of the Huanghe River in China is estimated at 1.1×10^9 tons, an order of magnitude greater than some 2000 years ago when human influences in the drainage basin were far less.

Applications to Past and Future: The stratigraphy of flood-plain and terrace deposits can yield a history of past stream changes [see sediment sequence and composition].

Subsurface temperature regime

Significance: The thermal regime of soils and bedrocks exercises an important control on the soil ecosystem, on near-surface chemical reactions (e.g. involving groundwater), and on the ability of these materials to sequester or release greenhouse gases. It may affect the type, productivity and decay of plants, the availability and retention of water, the rate of nutrient cycling, and the activities of soil microfauna. It is also of major importance as an archive of climate change, indicating changes in surface temperature over periods of up to 2-3 centuries, for example in regions without a record of past surface temperatures. In permafrost, the ground temperature controls the mechanical properties of the soils, especially during the freeze-thaw transition in the active layer.

Human or Natural Cause: The subsurface temperature regime reflects both the natural geothermal flux from the Earth's interior and the surface temperature. The latter can be modified by human actions, such as land clearing, wetland destruction, agriculture, deforestation, flooding of land for reservoirs, or development of large settlements that give rise to a 'heat island' effect.

Applications to Past and Future: Inversions of subsurface temperature profiles can provide a record of surface temperature, especially over the last 200-300 years, and a reliable indication of average surface temperatures of the past. Deep borehole records can yield records back 10,000 years or more.

Surface displacement

Significance: Most surface displacements have but minor effects on landscapes and ecosystems. However, there are exceptions, such as where drainage channels are suddenly displaced by faults, or where seismically-induced uplift raises intertidal ecosystems above sea-level. Moreover, extraction of fluids beneath urban areas can induce land subsidence (as in Bangkok, Mexico City, Shanghai, and Venice) and cause flooding, especially of coastal communities near sea-level. Subsidence damages buildings, foundations and other built structures: in the Houston-Galveston area of Texas, movements on more than 80 surface faults due to regional subsidence have caused millions of dollars of property damage.

Human or Natural Cause: Surface displacements are natural phenomena associated with plate movements, glacial rebound, and faulting, but human activities such as extraction of groundwater, oil and gas can also induce surface subsidence.

Applications to Past and Future: Measured trends of slow regional subsidence, uplift or lateral displacement can be used as a basis for predicting long-term consequences. Underground cavities liable to subsidence may be detected by gravity surveys.

Surface water quality

Significance: Clean water is essential to human survival as well as to aquatic life. Most is used for irrigation, with lesser amounts for municipal, industrial, and recreational purposes: only 6% of all water is used for domestic consumption. An estimated 75% of the populations of developing nations lacks adequate sanitary facilities, and wastes are commonly dumped into the nearest body of flowing water. Pathogens such as bacteria, viruses and parasites make these wastes among the world's most dangerous environmental pollutants: water-borne diseases are estimated to cause about 25,000 deaths daily. Water quality data are, thus, essential for the implementation of responsible water quality regulations, for characterizing and remediating contamination, and for the protection of the health of humans and aquatic organisms.

Human or Natural Cause: The water quality of a lake, reservoir or river can vary in space and time according to natural morphological, hydrological, chemical, biological and sedimentological processes (e.g. changes of erosion rates). Pollution of natural bodies of surface water is widespread because of human activities, such as disposal of sewage and industrial wastes, land clearance, deforestation, use of pesticides, mining, and hydroelectric developments.

Applications to Past and Future: Surface water does not preserve an archive of past changes because of rapid flow and mixing rates. However, it is important to recognize that there are close links between the chemistry of surface water and that of the bottom sediments in contact with the water. Thus, analysis of the sediment column can provide invaluable data about past trends in water quality [see sediment sequence and composition]. Increasing or decreasing trends in key parameters can warn of approaching thresholds requiring remedial action.

Volcanic unrest

Significance: Natural hazards associated with eruptions of the world's 550 or so historically active volcanoes pose a significant threat to about 10% of the world's population, especially in densely-populated circum-Pacific regions. By the year 2000, more than half a billion people will be at risk. Before 1900, two indirect hazards - volcanogenic tsunamis and post-eruption disease and starvation - accounted for most of the eruption-associated human fatalities. In the 20th century, however, direct hazards related to explosive eruptions (e.g. pyroclastic flows and surges, debris flows, mudflows) have been the most deadly hazards.

Human or Natural Cause: Volcanism is a natural process which has operated since the Earth was formed. Although a few attempts have been made to divert lava flows, humans have had no influence whatsoever on the underlying causes of volcanism.

Applications to Past and Future: During the past several decades, knowledge about how volcanoes work has expanded greatly. This increased knowledge has led not only to a better understanding of the eruptive process and products of previous volcanic events, but also to a sharper recognition of the need for multi-disciplinary, integrated field and laboratory studies. Even though considerable progress has been made in the forecasting of non-explosive eruptions at some well-monitored volcanoes (e.g. dome-building events at Mount St. Helens in the USA), the prediction of the onset and size of explosive eruptions remains elusive. Because no two volcanoes behave exactly alike, monitoring and related studies must be done at many more volcanoes before a predictive capability for explosive eruptions can be achieved.

Wetlands extent, structure and hydrology

Significance: Wetlands are areas of high biological productivity and diversity. They provide important sites for wildlife habitat and human recreation. Wetlands mediate large and small-scale environmental processes by altering downstream catchments. The dissolved carbon burden of wetlands may affect downstream waters, eg. by acid drainage. Wetlands can affect local hydrology by acting as a filter, sequestering and storing heavy metals and other pollutants, such as Hg, and serving as flood buffers and, in coastal zones, as storm defences and erosion controls.

Wetlands can act as a carbon sink, storing organic carbon in waterlogged sediments. Even slowly growing peatlands may sequester carbon at between 0.5 and 0.7 tonnes/ha/yr. Wetlands can also be a carbon source, when it is released via degassing during decay processes, or after drainage and cutting, as a result of oxidation or burning. Globally, peatlands have shifted over the past two centuries from sinks to sources of carbon, largely because of human exploitation. Some models of future climate change suggest that widespread thawing of permafrost peatlands due to climate warming, may lead to further emissions of greenhouse gases such as methane [see frozen ground activity].

Human or Natural Cause: Wetlands develop naturally in response to morphological and hydrological features of the landscape. Their evolution can be affected by external factors such as climate change, landscape processes (e.g. coastal erosion) or human activity (draining, channelling of local rivers, water abstraction and impoundment, forest clearance). In some parts of the world, wetlands are increasingly being lost to drainage for agriculture or settlement or to harvesting for commercial purposes.

Applications to Past and Future: Wetlands can provide important archives of past climatic, hydrologic and vegetation changes, through pollen and diatom stratigraphy, acidification studies, isotopic analyses, etc. They will also exert a profound effect on future environments if presently sequestered materials, such as carbon dioxide and methane, are released. The paleoecological record can provide baseline trends for use in developing models for future management approaches and for predicting the consequences of environmental change.

Wind erosion

Significance: Changes in wind-shaped surface morphology and vegetation cover that accompany desertification, drought, and aridification are important gauges of environmental change in arid lands. Wind erosion also affects large areas of croplands in arid and semi-arid regions, removing topsoil, seeds and nutrients.

Human or Natural Cause: Eolian erosion is a natural phenomenon, but the surfaces it acts upon may be made susceptible to active wind shaping and transport by human actions, especially those, such as cultivation and over-grazing, that result in the reduction of cover vegetation.

Applications to Past and Future: Differential erosion by wind in the past may be detected through study of buried soil horizons developed on ancient erosional surfaces, which formed during dry (wind erosion) to wet (soil formation) climatic cycles.

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